



Comparing the infiltration potentials of soils beneath the canopies of two contrasting urban tree species

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ABSTRACT

With ongoing urbanization and climate change our cities are continuously becoming warmer and susceptible to flash flooding. A wide array of green infrastructure including urban trees is getting attention to mitigate those problems; however, magnitude, patterns and processes of hydrological functional capacity of different tree species at micro-scales are largely unknown. We measured morphology, above and below ground growth of two ecologically contrasting street tree species at two streets in Munich, Germany: *Robinia pseudoacacia* L. and *Tilia cordata* Mill. during 2016–17. Additionally, tree transpiration, meteorological and edaphic variables including soil hydraulic conductivity was measured on two streets. Overall the soil physical properties including bulk density, particle size distribution and meteorological variables were not significantly different at the two sites. A higher soil infiltration rate (0.42 cm/min) under the canopies of *R. pseudoacacia* compared to the *T. cordata* (0.29 cm/min) was mainly attributed to the higher annual growth rate of *R. pseudoacacia* and showed a significant correlation ($r = 0.62$) with infiltration rate. Subsequently, *R. pseudoacacia* showed increased fine root biomass compared to *T. cordata* (121 g/m² and 27 g/m² respectively). However, *T. cordata* trees transpired three times more compared to *R. pseudoacacia* which indicated that they might have a deeper rooting system. The study showed that fast growing species such as *R. pseudoacacia* can enhance infiltration through its intense fine rooting system creating channels in the upper soil. Moreover, grass cover also plays a role both in infiltration and ground evapotranspiration compared to the built surfaces and can enhance the processes if planted in combination with less water using species. Secondly, higher root biomass and infiltration further away from the tree trunk suggest a need for larger tree planting pits whereas species such as *T. cordata* are better suited in paved cut-out pits inducing vertical rooting depth.

1. Introduction

With increasing urbanization we are continuously changing our landscapes and altering ecological processes to make our cities warmer (Gill et al., 2007; Oke, 1989; Rahman et al., 2011) and increasing rainfall runoff (Armson et al., 2013; Elliott et al., 2018). These problems will be exacerbated with the additional effects of climate change. Recently increased attention has been given to green infrastructure to enhance natural hydrological processes in the built environment (Elliott et al., 2018). However, the success would be dependent on its hydraulic functional capacity: the amount of water that can be captured and stored (Mullaney et al., 2015) as well as evapotranspired to cool the boundary layer (Rahman et al., 2017a). The great majority of

vegetation in urban areas grown in patches of soil in streets is essentially disconnected from the urban drainage network but can be considered to act hydrologically in parallel with it. Firstly, individual trees can intercept (directly through their leaves and branches) between 14 and 44% of the precipitation (Livesley et al., 2014; Xiao et al., 2000), direct towards stem flow (running down the stems or trunk) between 0.3 and 22.8% of the precipitation (Livesley et al., 2014; Schooling and Carlyle-Moses, 2015) and infiltrate the remaining water towards sub-surface soil (Armson et al., 2013; Elliott et al., 2018). Secondly, tree roots can influence deeper percolation and filter pollutants from runoff (Berland et al., 2017; Kuehler et al., 2017).

Canopy interception and stem flow of trees vary according to tree attributes, phenology and meteorological conditions. Among tree

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attributes: tree size, leaf area, leaf and branch angle, smoothness are most important (Berland et al., 2017; Xiao and McPherson, 2016). Conifers generally store more water than broadleaved trees (Xiao and McPherson, 2016). Even within the broadleaved trees, Van Stan et al. (2015) showed that *Liriodendron tulipifera* intercept 150 L of water more than the same sized *Fagus grandifolia* trees per storm event and within the same genus, Livesley et al. (2014) showed 15% difference in canopy interception of two different *Eucalyptus* species depending on the leaf area index. Overall open grown urban trees can intercept more than trees in woodland settings (Kuehler et al., 2017) especially where rainfall intensity is relatively low (Asadian and Weiler, 2009) such as in temperate Europe. In terms of absolute values, individual tree canopies can only retain the first 2–4 mm of rainfall (Livesley et al., 2014; Xiao et al., 2000). With impervious surfaces or compacted soils in urban areas even 2–4 mm rainfall can cause runoff (Pandit and Heck, 2009). Modern cities usually compact the ground surfaces before they construct buildings, roads and so on to improve the structural stability (Kuehler et al., 2017). Consequently, the infiltration rates on sandy soils can be reduced up to 99% (Gregory et al., 2006). Moreover, this process of decreased infiltration hastens the speed at which water travels over the surfaces and thus increases both surface runoff and peak discharge rates (Armson et al., 2013). Tree roots can increase the water infiltration as well as percolation leading to higher available soil moisture for evapotranspiration (Kuehler et al., 2017). There is also a time lag between the different processes of water storage by trees: canopy interception loss is more relevant during the rain event (Armson et al., 2013) while transpiration influences soil moisture during the days or weeks between the rain events (Berland et al., 2017).

Evapotranspiration is the key component of the urban hydrologic cycle with up to 80% of the annual precipitation going to this hydrologic pathway (Cleugh et al., 2005). Therefore, water moved along the soil-plant-atmospheric continuum can play a significant role in runoff reduction and mitigation of the urban heat island through evaporative cooling (Peters et al., 2011; Rahman et al., 2014). However, we are not aware of any study that specifically documented the role of individual urban trees in quantifying the transpirational cooling and soil infiltration potential. A more precise estimation of tree transpiration in urban areas is a precursor to maximize the effectiveness of urban greenery in storm water management (Berland et al., 2017). Likewise Pataki et al. (2011) emphasized the need for urban eco-hydrological studies including measurements for urban grown trees. Peters et al. (2011) showed a significant influence of plant functional types on the water budget. For instance, broadleaved species with differences in wood anatomy clearly showed significant differences in terms of tree transpiration (Bush et al., 2008). They may also have differences in rooting pattern (Ludwig et al., 2004) creating channels for water infiltration as well as deeper percolation. Therefore, different urban tree species with different ecological characteristics may have different influences on soil properties to modify the hydro-ecological benefits from urban green-spaces.

Water flows through the soil in two ways: saturated and unsaturated flow through fine roots and preferential flow through single or interconnected macro and micro-pores (Ghestem et al., 2011). Noguchi et al. (1999) reported that at least 70% of the macro-pores (> 2 mm) in the topsoil and 55% in the subsoil in a forest soil were associated with roots. Many research on forest conditions have shown how tree plantings increased the rooting density over the years which affected the porosity of the soil (Genenger et al., 2003; Lange et al., 2009). Significant differences of hydraulic conductivity of soils between species were found by Chandler et al. (2018) under forest condition. Bartens et al. (2008) showed how roots of the two deciduous species black oak (*Quercus velutina* Lam.) and red maple (*Acer rubrum* L.) penetrated the compacted clay loam soil and that the average infiltration rate increased to 153% compared to the unplanted controls. Depending on root extension, increased hydraulic conductivity was found beyond the crown radius (Chandler and Chappell, 2008). On contrary, Zadeh and

Sepaskhah (2016) showed that infiltration rate in 50 cm from the tree stem was 69–354% higher compared to soil outside the canopy drip line.

Despite the importance of urban greenspaces in hydrological function, minimal experimental data exist and those are related more towards the effect of planting design on soil infiltration (Elliott et al., 2018) but not regarding the influence of single trees or comparing the species differences. The influence of single trees has been investigated for soil moisture status (Ziemer, 1968) or rainfall interception (David et al., 2006). Clearly there is a knowledge gap regarding individual urban street trees' effect on water infiltration in soils. In this study we compared soil infiltration potential under the canopies of two ecologically contrasting but commonly planted broad leaved species *Tilia cordata* and *Robinia pseudoacacia* in Munich, Germany. *T. cordata* with diffuse porous wood anatomy and higher transpiration rate (Rahman et al., 2018) tend to have increased root length and volume on the lower soil horizons (Grabosky et al., 2009). On the other hand, *R. pseudoacacia* with ring porous wood anatomy and lower transpiration rate (Rahman et al., 2018) usually allocate more carbon to fine root biomass with horizontal shallow rooting (Reubens et al., 2009). We compared hydraulic conductivity (K) of grass lawns under individual trees with that of open grass land in the immediate vicinity to understand quantitatively a) if there is any difference in terms of soil infiltration rate under the canopies of the two species and between open grass surfaces and, b) what are the significant indicators of soil infiltration rate among tree growth, tree transpiration, meteorological or edaphic variables.

2. Methods

2.1. Study area

The study was conducted in Munich, the 3rd largest but the most densely populated city in Germany (4700 people/km²) with an increasing pressure on open space due to infill development (Bayerisches Landesamt für Statistik, 2017). The city is characterized by a warm temperate climate with substantial effects of urban heat island (UHI) with a monthly mean UHI intensity up to 6 °C (Pongracz et al., 2010). High surface sealing and low green shares (Pauleit and Duhme, 2000) particularly close to the city centre provide a low storm water retention capacity and vulnerability to flash flooding after heavy rain events (Zölch et al., 2017). Annual mean temperature for the city is 9.7 °C, with the average summer lows and highs being 9.4 °C (May) and 24.4 °C (July), respectively. Furthermore, Munich receives an average of 944 mm rainfall annually, with the majority of rain events occurring in the summer from May to August (DWD, 2017).

The eastern neighbourhood of Messestadt Riem (48°13'N, 11°69'E, at 520 m asl) was chosen following a dedicated field campaign (Fig. 1). The area was converted into a mixed urban neighbourhood after relocation of the airport in the early 1990's. Two nearby sites with east-west oriented streets were selected; one site with *Tilia cordata* and another with *Robinia pseudoacacia* trees. The selected tree species are two popular and commonly planted street trees with contrasting wood anatomy and water using behaviour. *T. cordata* is a diffuse-porous, anisohydric, shade-tolerant species with a low water use efficiency (Radoglou et al., 2009), *R. pseudoacacia* is characterized as ring-porous, isohydric, light-demanding and highly water using efficient species (Keresztesi, 1988; Roloff, 2013). The selected trees were free from any visual decay or damage, of similar age and similar branch free trunk height and planted on the same soil type. The *T. cordata* site with an area of around 4500 m² contains 67 *T. cordata* trees planted in two rows at each site of the square. The *R. pseudoacacia* site with an area of around 4000 m² had three rows with a large number of *R. pseudoacacia* trees. Trees were planted on lawns on both the sites and had 2–3 storey perimeter blocks distributed in a regular configuration along the North and South side of the streets. We choose 10 *T. cordata* trees at one

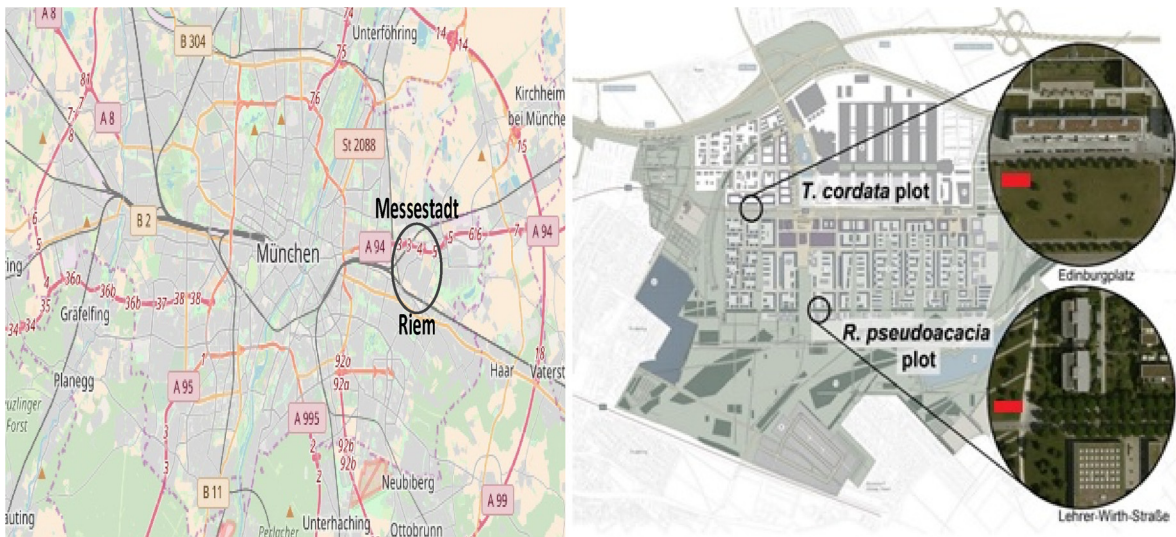


Fig. 1. The eastern neighbourhood of Messestadt Riem, Munich (left) with the two selected sites in Messestadt Riem (right). The red marked points indicate the control sites (source: Munich city council; processed) (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).



Fig. 2. *R. pseudoacacia* (left); *T. cordata* (middle) and control open grass site (right) with measuring devices.

straight row (8 m distance between trees), 1.5 m away from the asphalted street. In case of the *R. pseudoacacia* site we choose 10 trees in 2 rows of 5 trees each (8 m distance between rows and between trees) and only 1 row of trees was 1.5 m away from an asphalt street and the other row of trees was 1.5 m away from a cemented boundary wall (Fig. 2). There was no irrigation or pruning of trees at both the sites between May and October 2017. Moreover, to compare the soil infiltration potential we choose two open grass lawn sites outside of the tree influence zones (15 m apart from the tree rows).

2.2. Tree morphological measurements

We measured Diameter at breast height (DBH) using a dia-tape at a height of 1.3 m, tree height using a TruPulse 200 Laser Rangefinder, crown radii (r) in eight inter-cardinal directions using a measuring tape to calculate crown projection area ($CPA = \pi r^2$). Open surface area (OSA) of each tree was also measured in eight directions along the ground from the centre of the trunk to the last visible open, non-asphalted surface of the soil following Moser et al. (2017). LAI was estimated from hemispherical photographs captured in July 2016 using a Nikon CoolpixP5100 camera with fisheye lens and Mid-OMount. Moreover, each tree was cored to the heartwood at two opposing

directions (N–S) to estimate tree age and sap wood depth (SWD). Furthermore the cores were mounted on wooden boards and polished using finer sand papers progressively. The annual tree-ring width was measured with a Lintab digital positioning table with a resolution of 1/100 mm and afterwards the program TSAP-Win was used for data acquisition (Rinn Tech, 2010). Following a double detrending process and modified negative exponential curves and cubic smoothing splines (20 years rigidity, 50% wavelength cutoff, further averaged with Tukey's biweight robust mean) the tree-rings were detrended (Moser et al., 2018 submitted). Finally, the autocorrelation of every series was removed using autoregressive models (maximum order of 3).

For fine root biomass a brief field study was used first to determine the root biomass at distances of 20 cm, 40 cm, 60 cm, 80 cm and 1 m from the trunk. The highest concentration was found at 1 m from the trunk for both species. Accordingly in April 2018 we did soil coring down to 30-cm depth with a soil auger at 1 m and 3.5 m from the tree stem for every individual tree in the same direction. Before the soil coring the surfaces were cleared of grasses both below the tree canopy and at the control sites. Fine roots (< 2 cm) were filtered by sieves (2 mm) and separated by forceps in the laboratory. Then they were washed carefully and dried in the oven at 65 °C for 72 h. Afterwards the samples were weighed and fine root biomass ($g\ m^{-2}$) was estimated.

2.3. Meteorological data collection

Air temperature, air pressure, relative air humidity, precipitation, wind speed and direction were measured by installing Vaisala Weather Transmitters WXT520 at the two sites on top of a 3.5 m iron pole. Additionally, a CMP3 pyranometer and a PQS1 PAR sensors (Kipp & Zonen, Delft, The Netherlands) were installed at *R. pseudoacacia* site to measure global radiation and photosynthetically active radiation (PAR). At both the sites the stations were installed on top of open grass lawns close to the control sites. All the data were recorded continuously at a 15-min resolution from May 11 to October 30, 2017 on envLog remote data logger attached to one of our sampled trees (Fig. 2).

2.4. Tree transpiration and daily growth measurements

Tree transpiration was estimated using thermal dissipation probes (TDP) (Ecomatik, Dachau, Germany) introduced by Granier (1987). Pairs of 20 & 10-mm long and 2.0-mm diameter heating probes were inserted in the stem sapwood of 10 sampled *T. cordata* and *R. pseudoacacia* trees respectively on the north side of the trunk at 3–3.5 m height from the ground to deter theft or vandalism. Considering the radial variations in the sapwood area (Cermak and Nadezhkina, 1998), two pairs of longer needles were also inserted into the xylem depth of 20–40 and 40–60 mm on *T. cordata* trees. However, due to logistical constraints we could not investigate the pattern in sap flux density of *R. pseudoacacia* trees. The sensors were covered with reflective foil to minimize the influence of solar irradiance and connected to a CR800 data-logger (Campbell Scientific, UK) (Fig. 2). Five-minute means were calculated from the 30-s readings and stored by the data-logger. Temperature differences were converted to sap flux densities (J_s ; ml $\text{cm}^{-2} \text{min}^{-1}$) based on Granier's empirical calibration equation (Eq. (1)) (Granier, 1987):

$$J_s = 0.714 \left[\frac{\Delta T_M - \Delta T}{\Delta T} \right]^{1.231} \quad (1)$$

where ΔT_M is the maximum temperature difference when sap flow is assumed to be zero and ΔT is the difference between upper and lower sensor probes.

T. cordata trees showed a sharp decline of J_s from outer 20 mm to inner xylem of 40 mm (55%) and then a gradual decline (49%). Considering this variability, the total sap flow (SF) (ml $\text{tree}^{-1} \text{min}^{-1}$) for *T. cordata* (Eq. (2)) and *R. pseudoacacia* (Eq. (3)) were estimated by multiplying J_s with sap wood area (SA) following Rahman et al. (2017a):

$$\text{SF} = J_s \cdot \text{SA} / 2 + J_s \cdot 0.50 \cdot \text{SA} / 2 \quad (2)$$

$$\text{SF} = J_s \cdot \text{SA} \quad (3)$$

Daily stem growth of each tree was measured continuously with stem radius dendrometers (Ecomatik, Dachau, Germany), which were attached close to the sap flow sensors. The dendrometer measures the linear shifting of a small sensing rod fixed at the bark of the trunk (Moser et al., 2018 submitted). Raw data were recorded every 5 min from June 1, 2016 to May 30, 2017 and stored in the same data logger where sap flow sensors were attached.

2.5. Soil moisture potential, temperature and physical characteristics measurements

Soil matric potential and temperature were measured using Tensiomark (range pF0–pF7) (EcoTech, Bonn, Germany) installed at a distance of 3.5 m from the tree stem within the grass lawns at an angle of 45° through soil profile to the depth of 30 cm (details in Rahman et al. (2018)). At both sites measurement points were mostly shaded. However, due to logistical constraints, the measurements of soil moisture potential and soil temperature measurements were not

possible on control open grass lawns.

We collected soil samples using a soil augur of 30 cm length and 3 cm diameter at a distance of 1.5 m from each tree stem and control open grass site. The soil samples were weighted, dried at 60 °C for two weeks and weighed again to measure the soil water content and dry bulk density. Following the pretreatment for particle size analysis, CaCO_3 was destroyed by adding hydrochloric acid (HCl). Soluble salts and gypsum were washed out with an electrical conductivity of > 400 $\mu\text{S}/\text{cm}$. The coarser fractions were separated by sieving from the finer ones. For the determination of the finer fractions the sedimentation method was used.

2.6. Soil infiltration measurements

Unsaturated soil hydraulic conductivity (K) was measured on nine experiment days using a Decagon mini-disk infiltrometer (model S). Three of those days (Julian days 131, 144 and 271) were randomly selected. The remaining six trial days tracked the soil infiltration before and after precipitation events (Julian days 152, 159, 182, 185, 229 and 232). During each trial day, the two infiltrometers were placed simultaneously at 1.5 m distance apart from each other close to the tree stem (1 m) (I_{1m}) and two at drip line (3.5 m from the tree stem) ($I_{3.5m}$) of each tree. Additionally, at two control open grass sites (Fig. 2), four measurements at each site were taken. The suction of -2 cm was applied for sandy loam soil (according to the manual of Decagon, 2016). The changes on the water levels were recorded for eight minutes. Cumulative depth of water infiltrating was plotted as a function of time and infiltration rate was approximated using Eq. (4) (Zhang, 1997).

$$I = C_1 t + C_2 \sqrt{t} \quad (4)$$

where: C_1 , C_2 = fitting constants, t = time.

The hydraulic conductivity for the soil (K) was then computed using Eq. (5)

$$K = \frac{C_1}{A} \quad (5)$$

where A is derived from the van Genuchten parameters related to the soil type of the test area.

2.7. Statistical analysis

The software package R, version 3.2.1 (R Core Team, 2015) was used for statistical analysis. To investigate the difference between means, two-sampled t -test and analysis of variance (ANOVA) with Tukey's HSD test were used. In all the cases the means were reported as significant when $p < 0.05$. To assess the influence of measured meteorological, edaphic and tree morphological data on soil cumulative infiltration capability Spearman's rank correlation test was carried out.

3. Results

3.1. Tree morphological and soil characteristics

T. cordata trees were significantly older with higher LAI, sap wood depth and area but had significantly lower crown projection area, crown radius, crown volume, height and DBH compared to *R. pseudoacacia*. Open surface area at both sites was not significantly different (Table 1). Regarding the soil physical characteristics; bulk density at both sites and at the control was not different as well as the average sand, silt or clay distribution. However, soil at the *R. pseudoacacia* site showed a significantly higher amount of coarse sand compared to *T. cordata* and the control site, and soil at the *T. cordata* site showed a higher amount of medium silt than the *R. pseudoacacia* site (Table 2).

Table 1

Average morphological characteristics of trees and open surface area (OSA) of two sites (CPA = crown projection area; CR = crown radius; CV = crown volume; LAI = leaf area index; SWD = sap wood depth; SWA = sap wood area) (*at the $\alpha < 0.05$, **at the $\alpha < 0.01$, ***at the α -level < 0.001).

Species	Age (years)	CPA (m ²)	OSA (m ²)	CR (m)	CV (m ³)	DBH (cm)	Height (m)	LAI	SWD (cm)	SWA (cm ²)
<i>T. cordata</i>	36**	35	203	3.32	250	23.7	10.6	3.64*	7.15***	364***
<i>R. pseudo-acacia</i>	32	52**	198	4.03 **	460**	27.4*	12**	2.61	1.82	155

3.2. Micro-climatic differences

Global radiation peaked to around $21 \text{ MJ m}^{-2} \text{ d}^{-1}$ in June and started to decline to $20 \text{ MJ m}^{-2} \text{ d}^{-1}$ in July, and gradually to around $10 \text{ MJ m}^{-2} \text{ d}^{-1}$ in October. Over the months of May to October 2017 precipitation was not significantly different at two sites with average precipitation per day of 3.24 mm at the *R. pseudoacacia* and 3.33 mm at *T. cordata* site, as well as the air temperature and VPD. However, average wind speed 1.21 m s^{-1} compared to 1.04 m s^{-1} ($t = -16.85$, $df = 31585$, $p < 0.001$) was significantly higher at *T. cordata* site than *R. pseudoacacia* (Fig. 3).

3.3. Soil moisture and soil temperature

Over the months of May to October 2017 average soil moisture potential under the canopies of *T. cordata* was significantly more negative (-0.34 MPa) compared to the soil under the canopies of *R. pseudoacacia* (-0.11 MPa) (Fig. 4). Soil moisture potential under *T. cordata* trees peaked to the maximum value of -1.34 MPa compared to -0.63 MPa under the canopies of *R. pseudoacacia*. Consecutive rainy days (Julian days 204–206) amounting around 39 mm followed by 33 mm of rainfall on Julian day 207 (Fig. 3) might have explained the big drop of soil moisture potential during that particular date (Fig. 4). Similarly, the average soil temperature under the canopies of *T. cordata* was significantly higher (17.4°C) compared to the soils under the canopies of *R. pseudoacacia* (15.8°C). Soil temperature under the *T. cordata* trees peaked to the maximum value of 22.5°C compared to 21.3°C under the canopies of *R. pseudoacacia* (Fig. 4).

3.4. Above and below ground growth

The growth pattern of two species was significantly different (Fig. 5). *R. pseudoacacia* started to grow later in the year than *T. cordata* and therefore in May, *T. cordata* showed significantly higher diameter growth than *R. pseudoacacia*. In June there was no significant difference in growth between two species, however, from July to November *R. pseudoacacia* showed higher growth rates than *T. cordata*. Overall in 2016/17 tree stem diameter of *R. pseudoacacia* grew 45% more than *T. cordata* (5 mm compared to 3.4 mm).

Over the long term, annual DBH increment showed that *R. pseudoacacia* grew significantly more than *T. cordata* (5.06 compared to 4.02 mm yr^{-1}) ($t = 0.62$, $df = 11$, $P < 0.01$) (Fig. 6a). In case of root biomass, fine root biomass was higher at 3.5 m from the tree trunk compared to 1 m for both the species although not statistically

significant. However, fine root biomass of *R. pseudoacacia* was more than 4 times higher than *T. cordata* (121 compared to only 27 g m^{-2}) (Fig. 6b).

3.5. Tree transpiration

Tree transpiration was not significantly different between the three measured months for *T. cordata* trees. However, for *R. pseudoacacia* tree transpiration was significantly higher during June and July compared to May 2017 (Fig. 7). Overall, tree transpiration of *T. cordata* was more than three times higher than *R. pseudoacacia* (around 1500 liters per tree per month compared to approximately 400 liters for *R. pseudoacacia*).

3.6. Soil infiltration

The cumulative soil infiltration at 3.5 m under the canopies of *R. pseudoacacia* was significantly higher compared to 1 m of *R. pseudoacacia*, 1 m and 3.5 m of *T. cordata* as well as control site (Fig. 8). Cumulative infiltration at 1 m from *T. cordata* trunk showed the lowest values until the eighth minute.

Overall there was a significant difference among the soil infiltration rate and soil hydraulic conductivity (K) under the two different tree species and control (F (1, 357) = 6.59, $p < 0.05$; F (1, 104) = 19.13, $p < 0.001$ respectively) (Fig. 9). Further Tukey's post hoc analysis showed that soil infiltration rate and K was significantly higher both under the canopies of *R. pseudoacacia* (mean = 0.42 cm min^{-1} and $8.30 \times 10^{-3} \text{ cm s}^{-1}$) and in control sites (mean = 0.33 cm min^{-1} and $8.60 \times 10^{-3} \text{ cm s}^{-1}$) than the soils under the canopies of *T. cordata* (mean = 0.29 cm min^{-1} and $7.06 \times 10^{-3} \text{ cm s}^{-1}$). Both K and infiltration rate were significantly higher at 3.5 m compared to 1 m from the tree trunk.

3.7. Relationship between soil infiltration and tree growth, transpiration, meteorological and edaphic variables

Overall soil infiltration was negatively correlated with the tree transpiration although not statistically significant. Both above and below ground growth were positively correlated with soil infiltration. However, annual DBH increment showed a significant relationship with soil infiltration (Fig. 10). Among the meteorological variables precipitation showed a positive correlation with soil infiltration whereas global radiation showed a negative correlation although not statistically significant. Among the edaphic variables soil temperature showed a

Table 2

Soil characteristics under two species and at open control area (*at the $\alpha < 0.05$, **at the $\alpha < 0.01$, ***at the α -level < 0.001).

Soil under the species	Bulk density (g cc ⁻¹)	Sand			Silt (0.06–0.2 mm) (%)	Silt			Clay (< 0.002 mm) (%)
		Coarse sand (0.6–2 mm) (%)	Medium sand (0.2–0.6 mm) (%)	Fine sand (0.06–0.2 mm) (%)		Coarse silt (0.02–0.06 mm) (%)	Medium silt (0.006–0.02 mm) (%)	Fine silt (0.002–0.006 mm) (%)	
<i>T. cordata</i>	1.60	10.83	13.07	12.07	36.0	16.87	14.00	12.87	49.7
<i>R. pseudo-acacia</i>	1.74	17.93**	17.90	14.57	50.4	14.50	19.97*	11.63	40.13
Control	1.64	12.40	16.10	11.88	40.4	16.33	16.60	9.53	42.45

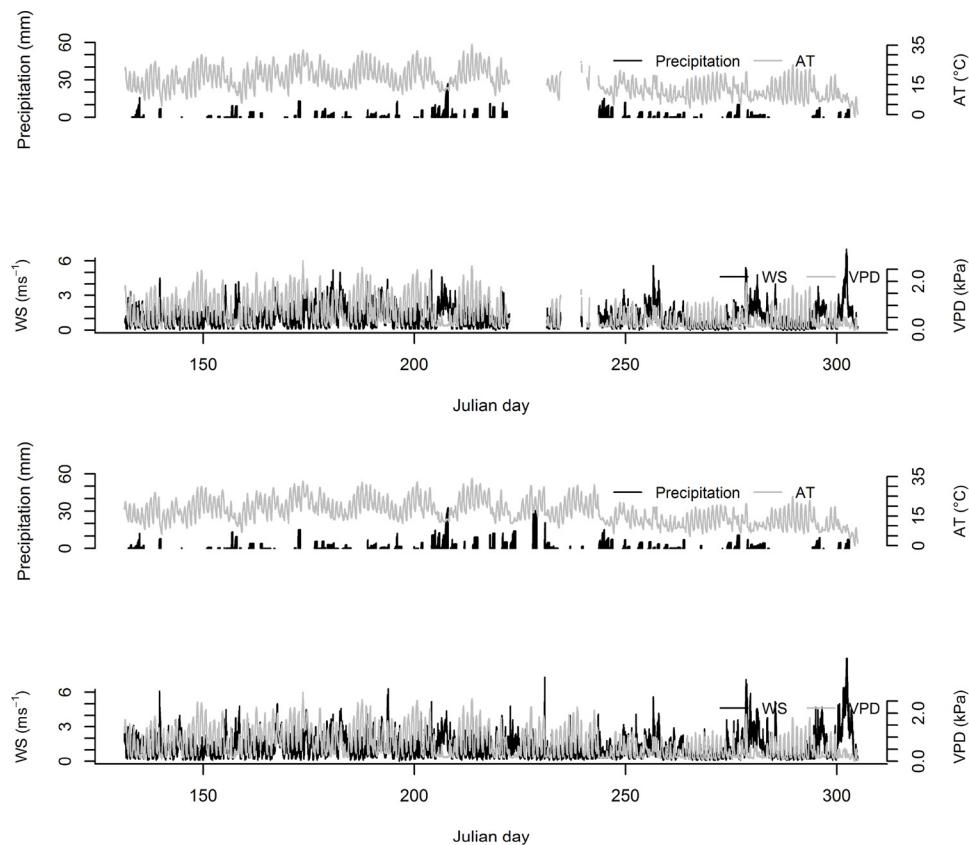


Fig. 3. Precipitation, air temperature (AT), wind speed (WS) and vapour pressure deficit (VPD) of *R. pseudoacacia* (a & b) and *T. cordata* (c & d) site (missing values are due to vandalism and technical errors).

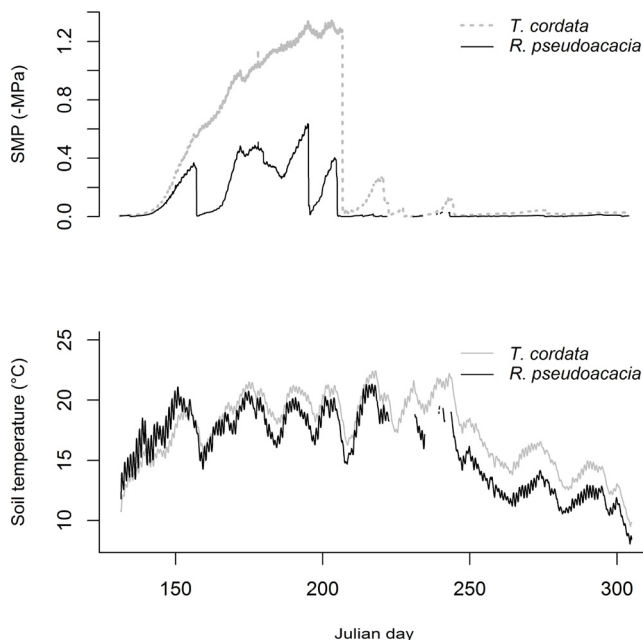


Fig. 4. Soil moisture potential (SMP) and soil temperature (ST) at 3.5 m from the tree trunk of *R. pseudoacacia* and *T. cordata* trees between Julian days 131 and 304 of the year 2017 (missing values are due to vandalism and technical errors).

comparatively higher negative correlation than soil moisture potential; however, the correlation was not statistically significant.

4. Discussions

The study showed a good agreement of tree eco-physiological responses with the meteorological and edaphic variables. *R. pseudoacacia* started their leaf flush late, showed higher daily growth than *T. cordata* starting from July and a gradual increase in transpiration towards the late summer. Increasing solar radiation, vapour pressure deficit, precipitation until mid-summer (July) also influenced the soil moisture potential, soil temperature as well as tree transpiration. In general, distribution of soil particles and bulk density at the three sites (*R. pseudoacacia*, *T. cordata* and control) as well as meteorological variables were not significantly different. Significantly higher DBH and root growth of *R. pseudoacacia* trees compared to the *T. cordata* therefore can be attributed to the contrasting life strategies of the species. Diffuse porous species - *T. cordata* along with their higher leaf area index showed three times higher amount of water loss and consequently higher boundary layer cooling compared to the ring porous species - *R. pseudoacacia*. However, better water use efficiencies of *R. pseudoacacia* consequently resulted in higher above and below-ground growth and more macro and micro-pore spaces in the surface soil to have significantly higher soil infiltration rate especially towards the crown periphery of trees than close to the tree trunks.

4.1. Micro-climatic differences

The flow of water from the above ground into the subsurface is a soil property and therefore a direct relationship of meteorological variables cannot be expected as shown in the current study (Fig. 10). Rather meteorological variables can define the atmospheric demand which

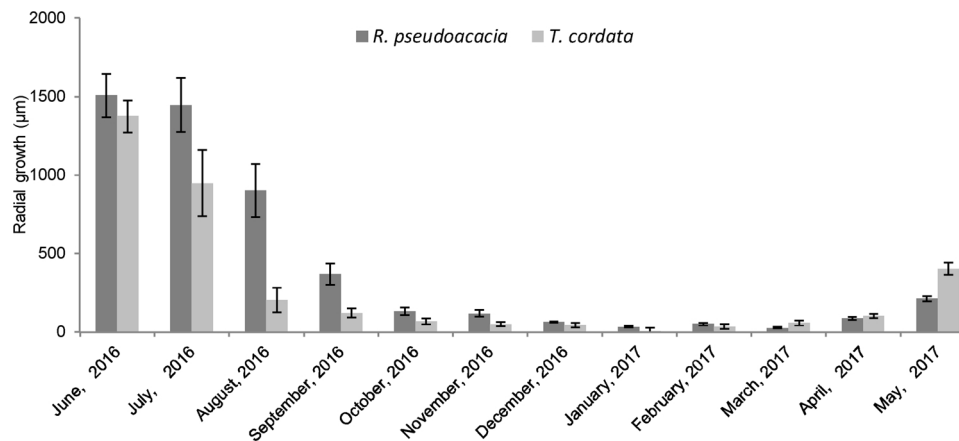


Fig. 5. Diameter increment of *R. pseudoacacia* and *T. cordata* over one year (June 2016 to May 2017).

significantly influence the tree transpiration. Research such as Rahman et al. (2017a) showed that sap flux density is an artefact of vapour pressure deficit (VPD), global radiation (GR), wind speed (WS), and soil temperature (ST) which can explain 78% of the variation on the measured sites at the city centre of Munich. Again tree transpiration can have a negative feedback on daily growth pattern (Moser et al., 2017) and it can also influence the soil-plant-atmospheric continuum or soil infiltration potential as shown in this study (Fig. 10). In the current study, GR was only measured in one site; however with a similar sky view factor (Rahman et al., 2018) at two sites it is arguable that the GR was similar at the two sites. Nevertheless, edaphic variables such as ST and meteorological variables such as precipitation which influence soil moisture status showed strong relationships with infiltration rate. In this study, the most significant meteorological variable in terms of soil infiltration- precipitation amount was not different at the two sites.

The biggest differences between the two sites were evident in terms of soil temperature (ST) and soil moisture potential (SMP): ST was significantly higher and SMP was significantly more negative at the *T. cordata* site throughout the experiment. However, in our study soil physical characteristics under the canopies of both *T. cordata* and *R. pseudoacacia* as well as at the control sites were not significantly different. Therefore, it is more likely that the tree physiological characteristics determines the tree morphology and below ground micro-spaces and root channeling to determine surface infiltration or sub-

surface percolation rate.

4.2. Tree growth and physiology

The studied species showed contrasting tree morphological characteristics. Even though *R. pseudoacacia* trees were younger in age, they showed higher crown dimensions, tree height, DBH compared to *T. cordata*. Only LAI was significantly higher for *T. cordata* trees. These findings are in line with the fact that *T. cordata* is a shade-tolerant species that grows with intermediate speed while *R. pseudoacacia* is a light-demanding, fast growing and nitrogen-fixing species (Keresztesi, 1988; Roloff, 2013). Comparatively late leaf flush of *R. pseudoacacia* is associated with the xylem anatomy of the species since ring porous species usually initiate replacing the caviated vessels with new xylem before new leaves can be supplied with water (Panchen et al., 2014). On the other hand, diffuse porous species such as *T. cordata* can afford leaf flush earlier due to little risk of frost damage to the vessels and have the advantage of better growth at the early summer or even late spring (Michelot et al., 2012). Research such as Rötzer et al. (2017) also used dendrometers to measure the daily growth pattern of ring porous spruce and diffuse porous beech under different treatments at the Northeast of Munich within the Kranzberg Forest. The results of the current study is completely in agreement with Rötzer et al. (2017) with a strong increase in spring due to beginning of the growth period comparable to

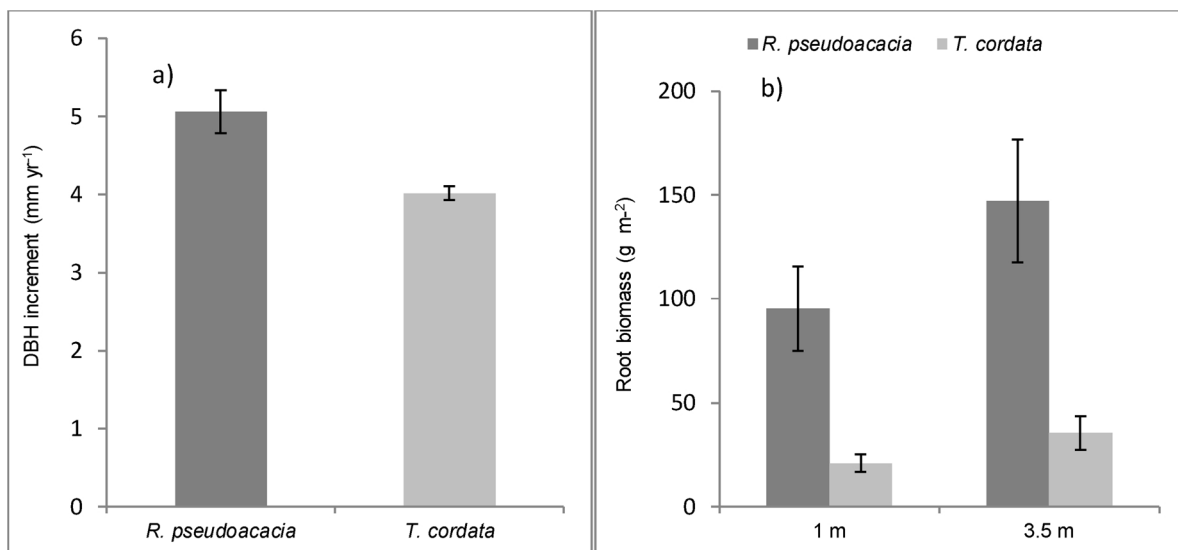


Fig. 6. Annual DBH increment of *R. pseudoacacia* and *T. cordata* (1986–2017) (a) and root biomass of *R. pseudoacacia* and *T. cordata* (b) 1 m and 3.5 m from tree trunk.

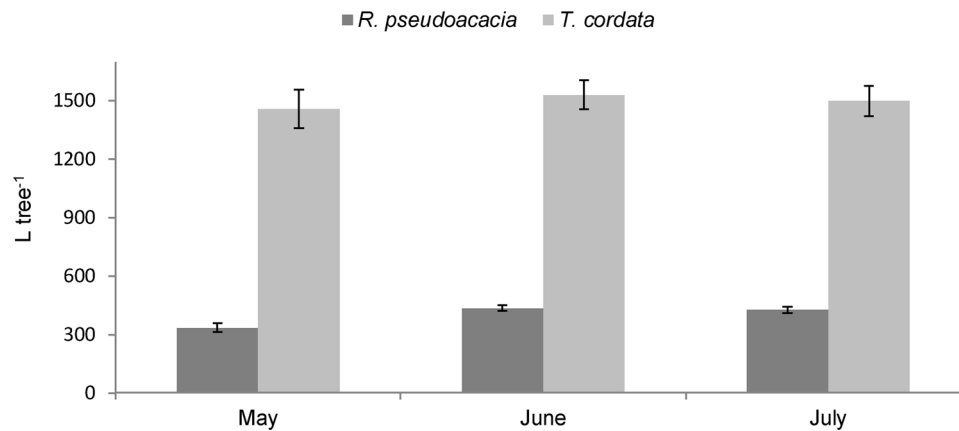


Fig. 7. Total sap flow per tree from *R. pseudoacacia* and *T. cordata* trees during May, June and July 2017.

the growth of *T. cordata* and *R. pseudoacacia* in early summer. Accumulation of every year's higher growth consequently showed higher annual DBH increment as shown in this study (Fig. 6a).

Regarding below-ground carbon allocation, Deng et al. (2014) reported fine root biomass of *R. pseudoacacia* at a forest plantation site of 163 g m^{-2} at a depth between 0–40 cm which is close to our reported values at least at 3.5 m. Reubens et al. (2009) also reported that *R. pseudoacacia* allocate relatively more to fine root biomass and horizontal shallow roots. *T. cordata* on the other hand tend to have increased root length and volume on the lower soil horizons (Grabosky et al., 2009). We did not investigate the rooting depth but with the fine root biomass it is likely that they have differences in radial fine root distribution in the soil (Meinen et al., 2009) to support the three times higher transpiration rate by the *T. cordata* trees. On the other hand, it appears that the consistent rate of transpiration of *R. pseudoacacia* was supported by the vital and large fine root system even in drought (Kocher et al., 2009). Although both *R. pseudoacacia* and *T. cordata* species are known to be drought-tolerant (Kocher et al., 2009; Roloff, 2013), seedlings of *T. cordata* either in street conditions (Whitlow et al., 1992) or in climate chambers (Haeberle et al., 2016) showed drought avoidance characteristics in drought conditions. Moreover, with matured *T. cordata* grown in forest conditions Kocher et al. (2009) showed that leaf conductivity was reduced substantially with increasing vapour pressure deficit and decreasing soil matric water potential which would be elements of a drought avoiding strategy.

The results of the sap flow rates of both *T. cordata* and *R.*

pseudoacacia is in line with previous studies in Munich (Rahman et al., 2018, 2017a; Rahman et al., 2017b). This is mainly attributed to the xylem anatomy of the two species (Bush et al., 2008; Peters et al., 2011). With significantly higher sap wood area and LAI, the diffuse porous *T. cordata* supported almost double the sap flux density (data not shown) than *R. pseudoacacia*. Nonetheless, Moser et al. (2018 submitted) showed how higher water use efficiencies of *R. pseudoacacia* contributed to the higher growth rate compared to the *T. cordata*. Naturally the size of the tree is the most important factor when determining the total amount of water removal from the system regardless of the transpiration rate (Bartens et al., 2009). Until now the main contribution of urban trees in terms of reduction of surface water runoff is highlighted as interception and evapotranspiration (Armson et al., 2013; Zölch et al., 2017); however, the missing link is the soil infiltration. Again soil-root-water interactions are complex dynamics to understand mainly due to the combined effects of transpiration and water evaporation from the soil surface beneath the tree canopies (Gadi et al., 2016).

4.3. Soil infiltration

In the current study we compared the soil infiltration of open grass lawns topsoil (control) with that of grass lawns beneath individual trees. Secondly, the study of individual trees allows us to better understand the influencing sphere of two contrasting species along with the distances from the main stem. The open surface area (OSA)

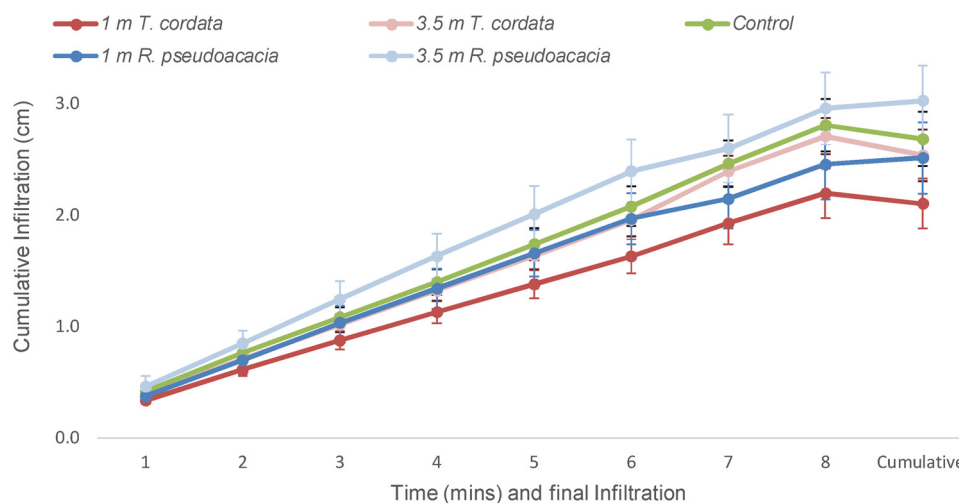


Fig. 8. Cumulative infiltration at 1 m and 3.5 m under the canopies of *R. pseudoacacia* and *T. cordata* trees and on control sites over the 8 min during the sampling days.

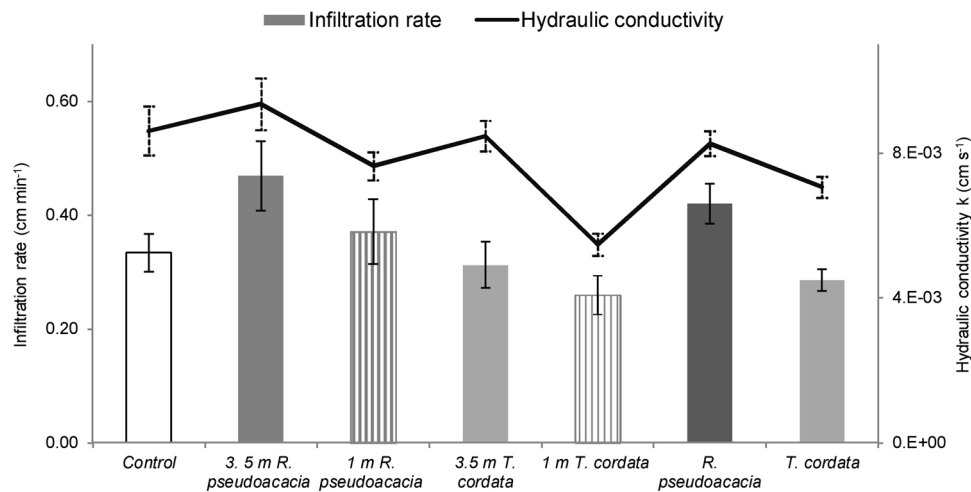


Fig. 9. Infiltration rate and hydraulic conductivity of soil at control, at 3.5 m, 1 m as well as the average of 1 m and 3.5 m under the canopies of *R. pseudoacacia* and *T. cordata*.

(Table 1) was similar for both the sites. Therefore, the horizontal proliferation of fine roots was not subjected to different rooting volumes. The control grass lawns were also selected intentionally to have equal pedestrian traffic as such beneath the individual trees. The study by Chandler and Chappell (2008) showed that tree hydraulic properties are often masked by the higher intensity of land use such as grazing in forest or foot traffic in urban condition. Thus any differences that occurred in infiltration rates were mainly due to the tree rooting attributes. Particularly, significant differences in root characteristics, organic matter content and biological agents of creating macro pores have been highlighted between broadleaved and conifer trees (Reich et al., 2005) to explain differences in soil hydraulic conductivity between different species or sites. However, in an urban context abundance of biological agents or organic matter is lower compared to the natural sites (Harris, 1991). Our result of higher soil infiltration under the control grass lawns at least from the infiltration values of I_{1m} *T. cordata* is in agreement with the study of Kumar et al. (2012) that compared tree and grass buffer zones and found that soil infiltration was higher under grass.

Higher root biomass further away towards the open surface area in case of both *T. cordata* and *R. pseudoacacia* may be due to the fact that fine roots spread more outwards than towards the centre of the canopy in search of water (Perry, 1989). Therefore, research such as Cutler and Richardson (1989) pointed out how the root system of species such as oak extends their rooting system well beyond the canopy. Additionally, a reduction in hydraulic conductivity (Ks) with a factor of 5.4 directly beneath individual Sitka spruce (*Picea sitchensis*) compared with soil 2 m away from each tree were reported. Incorporating trees into urban

landscapes can substantially reduce storm water runoff by lessening compaction and increasing porosity and infiltration (Wheeler et al., 2002). Likewise one experimental study in Manchester, UK, showed that one small *Acer campestre* tree planted on the centre of a 9 m² asphalt plot can reduce surface runoff of the total catchment area by 62% and this reduction was largely attributed to infiltration into the tree pit (Armson et al., 2013). Yang and Zhang (2011) characterized 30 urban sites and found that urban lawns with trees have the highest infiltration rates. While comparing different surface types Armson et al. (2013) showed a 99% runoff reduction of grass lawns compared to asphalt. In the present study we did not study the sub-surface soil profile. Future studies including the investigation of deeper soil profile will thus provide more evidence on the rooting system and soil infiltration potential of different components of green infrastructure.

Planting of tree species with a complementary root system in grassy lawns can help to optimize surface runoff reduction and cooling benefits. Tree species such as *R. pseudoacacia* with their higher growth rate and fine root biomass can influence higher infiltration. At the same time, species such as *T. cordata* can influence deeper percolation and access a greater soil volume with more vertical rooting depth. With a higher crown spread, fissured bark and the sharp spines on the leaf stalks, *R. pseudoacacia* can induce higher interception and stem flow compared to *T. cordata* and therefore, ultimately positively influence the soil water storage. Moreover, *Robinia* and *Tilia* have different impacts on human thermal comfort on grass lawns and on paved spaces as shown in previous studies (Rahman et al., 2018). However, more research on species suitability and optimizing the ecosystem services in cities are absolutely important.

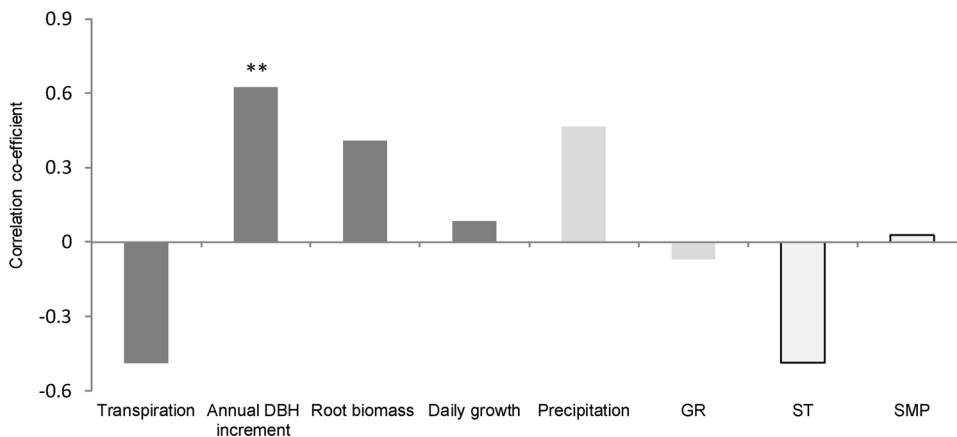


Fig. 10. Correlations between cumulative infiltration (cm) with transpiration (l day⁻¹), annual DBH increment (mm yr⁻¹), root biomass (g m⁻²), daily growth (μm day⁻¹); precipitation (mm day⁻¹), global radiation (GR) (MJ m⁻² d⁻¹); soil temperature (ST) (°C) and soil moisture potential (SMP) (MPa). Dark bars represent the tree transpiration and growth, the light colour bars represent meteorological and the light bars with black borders represent edaphic variables. Asterisks indicate a significant correlation (*at the $\alpha < 0.05$, **at the $\alpha < 0.01$, ***at the α -level < 0.001).

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